

Docket No. BPHOTO.003

LATERALLY COUPLED WAVE GUIDES

RELATED APPLICATIONS

The present application is related to, and claims
5 the benefit of priority of, co-pending provisional U.S.
Patent Application Serial No. 60/274,584 entitled
"Laterally Coupled Waveguides," filed on March 9, 2001,
which is hereby incorporated by reference in its
entirety.

10

BACKGROUND OF THE INVENTION

1. Technical Field:

The present application relates to laser diodes, and
15 more particularly to the coupling of multiple waveguides
in a laser diode system.

2. Description of Related Art:

Transmission of light through waveguides has been
20 pursued for many types of communications applications.
Light signals offer many potential advantages over
electronic signals. Light sources are commonly created
from semiconductor devices, and include semiconductor
devices such as LEDs (Light Emitting Diodes) and LDs
25 (Laser Diodes).

Optical fiber is the most commonly used transmission
medium for light signals. A single fiber is capable of
carrying several different modulated signals within it at
one time. For instance, wavelength division multiplexing
30 divides the used bandwidth of the fiber into different

Docket No. BPHOTO.003

channels (each channel containing a small range of wavelengths) and thus transmits several different wavelengths (or signals) of light at once. Using such a system requires sources for the different wavelengths.

- 5 More wavelengths on the fiber require more sources to be coupled to the fiber.

Efficient coupling of light into a fiber is simplified if the laser beam has a cross sectional profile that matches the profile of the fiber mode(s). Efficient
10 use of light for communications requires that the light have high temporal coherence. Efficient coupling of light to monomode guides requires spatial coherence. Spatial coherence requires the laser to operate in a single lateral and transverse mode. Temporal coherence requires
15 the laser to operate in a single longitudinal mode and implies a very narrow bandwidth, or range of wavelengths.

The most coherent semiconductor lasers use resonators based on grating feedback rather than Fabry-Perot resonators with reflective end facets. Distributed
20 feedback (DFB) lasers use a Bragg reflective grating covering the entire pumped length of the laser. An alternative to DFB lasers is the use of distributed Bragg reflectors (DBRs) located outside the pumped region.

In conventional DFB and DBR lasers, light is removed
25 through an end facet and the output beams have dimensions entirely controlled by the vertical (i.e., normal to the surface) (x) and lateral (y) size and the composition of the guiding structure. Such output beams are typically have too great a divergence for effective coupling to

Docket No. BPHOTO.003

optical fibers, or for other applications requiring beams with low divergence angles.

Beam dimensions (in at least one direction) larger than that available from laser facets may be obtained by
5 using a Bragg grating to couple light out of the waveguide normal (or at certain fixed angles) to the waveguide surface. So called second order Bragg gratings have a period equal to the wavelength of light of the guided mode. The second grating order of such a grating reflects
10 some of the light back in the waveguide plane while the first order couples some of the light normal to the plane. So called first order (Bragg) gratings have a period equal to one half the wavelength of light in the guided mode, reflect light in the waveguide plane, and do not couple
15 light out of the waveguide. First, second, and third order (etc.) gratings are sometimes referred to as being in resonance. A non-resonant grating couples light out of the waveguide at an angle to the normal and does not reflect any light in the waveguide plane.

20 US patent 5,970,081 to Hirayama et al. appears to show a laser with a distributed feedback (DFB) grating of second order or higher that claims to obtain a Gaussian shaped output beam by narrowing the waveguide or using a chirped grating at the outcoupling portion. They do not
25 seem to recognize that by so doing the resonant wavelength of the grating is altered along the length of the narrowing or chirping. This would be expected to result in an output which will fan in angle along the longitudinal direction rather than produce a simple Gaussian intensity
30 variation emitted normal to the plane as claimed. They do

Docket No. BPHOTO.003

not define the beam shape in the lateral direction. In all versions they choose second order outcoupling gratings which, absent a narrowing waveguide or chirp, would emit light perpendicular to the surface of the laser waveguide.

5 US patent 4,006,432 to Streifer et al. appears to show a grating out-coupled surface emitting DFB laser. The grating period may be chosen to be either resonant or not.

A paper by Bedford, Luo, and Fallahi titled Bow-Tie Surface-Emitting Lasers (IEEE Photonics Technology
10 Letters, Vol. 12, No. 8, Aug. 2000) appears to show a DBR laser with curved second order grating at the ends to couple light out of the waveguide. The same gratings are used for outcoupling and for reflecting the light within the waveguide. They mention the use of non-resonant
15 gratings in conjunction with reflector gratings if emission at other than the direction normal the waveguide plane is desired. The paper appears to show a flared resonator region which allows symmetric outcoupling from both ends of the laser. This facilitates two outputs that
20 are coherent with one another, with emission in the same direction. Such a device is meant to alleviate the complications of controlling the relative phase between the two emitters.

The Tiberio article (Facetless Bragg reflector
25 surface-emitting AlGaAs/GaAs lasers..., J. Vac. Sci. Technol., B9(6), 1991) appears to show a surface emitting laser diode that uses first order reflective gratings and either second order (or non-resonant) gratings for outcoupling. Thus, depending on the chosen grating period,

Docket No. BPHOTO.003

the outcoupled beam can be normal or at an angle to the surface.

US patent 6,064,783 to Congden appears to show a DBR laser with a grating assisted waveguide coupler that
5 couples light from the laser waveguide to a parallel fiber-like glass waveguide for later coupling to a fiber. Several different lasers are coupled to similar fiber-like glass waveguides in the figures. The fiber axis is parallel to the laser waveguides. This reference mentions
10 that this model is easily attached to a fiber through "butt coupling." The grating acts as a Quasi Phase Matching element to couple the light from the laser waveguide to the fiber-like glass waveguide.

The optical and electronic properties of a
15 semiconductor depend on the crystal structure of the device, which has led to investigative work into fabricating artificial structures or superlattices. By tailoring the crystal structure of a device during its fabrication, the optical and electronic properties can be
20 controlled. The crystal structures of such devices may be controlled, for instance, by molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD). Such techniques are capable of monolayer control (~5 angstrom) over the chemical composition of a crystal.

25 Other commonly used heterostructures are quantum wells, in which a single layer of one semiconductor is sandwiched between two layers of a larger bandgap material. Strain is produced by using an epitaxial layer with a different lattice constant than the substrate. This
30 strain has a dramatic effect on the properties of the

Docket No. BPHOTO.003

optical system. Among other things, it can allow bandgap tunability, reduced threshold current, and improved laser reliability.

Strain can also allow laser emission to have tailored
5 polarization. By using appropriate strain, one can produce light predominantly polarized as TE, or TM.

Docket No. BPHOTO.003

SUMMARY OF THE INVENTION

This application discloses a laser source and system for coupling multiple waveguides in a laser diode system.

5 In an example of a preferred embodiment, the source is a laser diode and has an active region with distributed Bragg reflectors at either end to reflect light within the cavity, and an outcoupling grating in the center or elsewhere within the cavity (defined by the end DBRs) of

10 the device which couples light out of the cavity. On either side of the outcoupling grating is a gain region with electrical contacts for supplying current. In some embodiments, the outcoupling grating may be at the end of a gain region with only a DBR and not a gain region on the

15 other side. Optically attached to the central waveguide are added waveguides which couple light into the central waveguide, preferably via evanescent coupling or grating assisted coupling. In an example of a two-cavity system, two added waveguides are optically attached to the central

20 waveguide. Each of the added waveguides has a reflector at one end, and the other end couples to the central waveguide near the outcoupling region of the central waveguide. Light generated in one of the added waveguides passes into the central waveguide at the coupling region.

25 Part of the light is outcoupled, part passes back into the other added waveguide, which is optically attached to the central waveguide on the other side of the outcoupling region with respect to the first of the added waveguides. Hence, the two added waveguide, plus the outcoupling

30 section of the central waveguide, comprise a second

Docket No. BPHOTO.003

cavity. This second cavity can generate light of a different central wavelength than the central waveguide, for example, by using reflective gratings that are of different period than those of the central waveguide.

5 The present innovations disclose a system capable of creating multiple beams of light. Each beam is of a different central wavelength, capable of being generated on chip and coupled into a single fiber, and emitted from a single outcoupling grating.

10 This basic laser diode design makes it easier to limit the length of the outcoupling grating to short lengths, on the order of about 10 microns. In previous designs where the outcoupler is outside the DBR laser
15 region, it becomes very difficult to outcouple 100% of the light in such a short distance. The light that is not coupled out is wasted and decreases device efficiency.

 The disclosed innovations, in various embodiments, provide one or more of at least the following advantages:

- 20 • low cost;
- device testing at the wafer level;
- emission at all wavelengths from 0.6-2.0 microns with existing and common material systems, with greater ranges possible;
- 25 • emission is easily extended to any wavelength as new material systems and laser designs mature and/or are developed;
- low drive currents;
- higher power capability than existing VCSELs;
- 30 • high efficiency;

Docket No. BPHOTO.003

- direct replacement for VCSELs;
- easily coupled to multi-mode and single-mode fibers.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
241
242
243
244
245
246
247
248
249
250
251
252
253
254
255
256
257
258
259
260
261
262
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280
281
282
283
284
285
286
287
288
289
290
291
292
293
294
295
296
297
298
299
300
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
341
342
343
344
345
346
347
348
349
350
351
352
353
354
355
356
357
358
359
360
361
362
363
364
365
366
367
368
369
370
371
372
373
374
375
376
377
378
379
380
381
382
383
384
385
386
387
388
389
390
391
392
393
394
395
396
397
398
399
400
401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
463
464
465
466
467
468
469
470
471
472
473
474
475
476
477
478
479
480
481
482
483
484
485
486
487
488
489
490
491
492
493
494
495
496
497
498
499
500
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
522
523
524
525
526
527
528
529
530
531
532
533
534
535
536
537
538
539
540
541
542
543
544
545
546
547
548
549
550
551
552
553
554
555
556
557
558
559
560
561
562
563
564
565
566
567
568
569
570
571
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
587
588
589
590
591
592
593
594
595
596
597
598
599
600
601
602
603
604
605
606
607
608
609
610
611
612
613
614
615
616
617
618
619
620
621
622
623
624
625
626
627
628
629
630
631
632
633
634
635
636
637
638
639
640
641
642
643
644
645
646
647
648
649
650
651
652
653
654
655
656
657
658
659
660
661
662
663
664
665
666
667
668
669
670
671
672
673
674
675
676
677
678
679
680
681
682
683
684
685
686
687
688
689
690
691
692
693
694
695
696
697
698
699
700
701
702
703
704
705
706
707
708
709
710
711
712
713
714
715
716
717
718
719
720
721
722
723
724
725
726
727
728
729
730
731
732
733
734
735
736
737
738
739
740
741
742
743
744
745
746
747
748
749
750
751
752
753
754
755
756
757
758
759
760
761
762
763
764
765
766
767
768
769
770
771
772
773
774
775
776
777
778
779
780
781
782
783
784
785
786
787
788
789
790
791
792
793
794
795
796
797
798
799
800
801
802
803
804
805
806
807
808
809
810
811
812
813
814
815
816
817
818
819
820
821
822
823
824
825
826
827
828
829
830
831
832
833
834
835
836
837
838
839
840
841
842
843
844
845
846
847
848
849
850
851
852
853
854
855
856
857
858
859
860
861
862
863
864
865
866
867
868
869
870
871
872
873
874
875
876
877
878
879
880
881
882
883
884
885
886
887
888
889
890
891
892
893
894
895
896
897
898
899
900
901
902
903
904
905
906
907
908
909
910
911
912
913
914
915
916
917
918
919
920
921
922
923
924
925
926
927
928
929
930
931
932
933
934
935
936
937
938
939
940
941
942
943
944
945
946
947
948
949
950
951
952
953
954
955
956
957
958
959
960
961
962
963
964
965
966
967
968
969
970
971
972
973
974
975
976
977
978
979
980
981
982
983
984
985
986
987
988
989
990
991
992
993
994
995
996
997
998
999
1000
1001
1002
1003
1004
1005
1006
1007
1008
1009
1010
1011
1012
1013
1014
1015
1016
1017
1018
1019
1020
1021
1022
1023
1024
1025
1026
1027
1028
1029
1030
1031
1032
1033
1034
1035
1036
1037
1038
1039
1040
1041
1042
1043
1044
1045
1046
1047
1048
1049
1050
1051
1052
1053
1054
1055
1056
1057
1058
1059
1060
1061
1062
1063
1064
1065
1066
1067
1068
1069
1070
1071
1072
1073
1074
1075
1076
1077
1078
1079
1080
1081
1082
1083
1084
1085
1086
1087
1088
1089
1090
1091
1092
1093
1094
1095
1096
1097
1098
1099
1100
1101
1102
1103
1104
1105
1106
1107
1108
1109
1110
1111
1112
1113
1114
1115
1116
1117
1118
1119
1120
1121
1122
1123
1124
1125
1126
1127
1128
1129
1130
1131
1132
1133
1134
1135
1136
1137
1138
1139
1140
1141
1142
1143
1144
1145
1146
1147
1148
1149
1150
1151
1152
1153
1154
1155
1156
1157
1158
1159
1160
1161
1162
1163
1164
1165
1166
1167
1168
1169
1170
1171
1172
1173
1174
1175
1176
1177
1178
1179
1180
1181
1182
1183
1184
1185
1186
1187
1188
1189
1190
1191
1192
1193
1194
1195
1196
1197
1198
1199
1200
1201
1202
1203
1204
1205
1206
1207
1208
1209
1210
1211
1212
1213
1214
1215
1216
1217
1218
1219
1220
1221
1222
1223
1224
1225
1226
1227
1228
1229
1230
1231
1232
1233
1234
1235
1236
1237
1238
1239
1240
1241
1242
1243
1244
1245
1246
1247
1248
1249
1250
1251
1252
1253
1254
1255
1256
1257
1258
1259
1260
1261
1262
1263
1264
1265
1266
1267
1268
1269
1270
1271
1272
1273
1274
1275
1276
1277
1278
1279
1280
1281
1282
1283
1284
1285
1286
1287
1288
1289
1290
1291
1292
1293
1294
1295
1296
1297
1298
1299
1300
1301
1302
1303
1304
1305
1306
1307
1308
1309
1310
1311
1312
1313
1314
1315
1316
1317
1318
1319
1320
1321
1322
1323
1324
1325
1326
1327
1328
1329
1330
1331
1332
1333
1334
1335
1336
1337
1338
1339
1340
1341
1342
1343
1344
1345
1346
1347
1348
1349
1350
1351
1352
1353
1354
1355
1356
1357
1358
1359
1360
1361
1362
1363
1364
1365
1366
1367
1368
1369
1370
1371
1372
1373
1374
1375
1376
1377
1378
1379
1380
1381
1382
1383
1384
1385
1386
1387
1388
1389
1390
1391
1392
1393
1394
1395
1396
1397
1398
1399
1400
1401
1402
1403
1404
1405
1406
1407
1408
1409
1410
1411
1412
1413
1414
1415
1416
1417
1418
1419
1420
1421
1422
1423
1424
1425
1426
1427
1428
1429
1430
1431
1432
1433
1434
1435
1436
1437
1438
1439
1440
1441
1442
1443
1444
1445
1446
1447
1448
1449
1450
1451
1452
1453
1454
1455
1456
1457
1458
1459
1460
1461
1462
1463
1464
1465
1466
1467
1468
1469
1470
1471
1472
1473
1474
1475
1476
1477
1478
1479
1480
1481
1482
1483
1484
1485
1486
1487
1488
1489
1490
1491
1492
1493
1494
1495
1496
1497
1498
1499
1500
1501
1502
1503
1504
1505
1506
1507
1508
1509
1510
1511
1512
1513
1514
1515
1516
1517
1518
1519
1520
1521
1522
1523
1524
1525
1526
1527
1528
1529
1530
1531
1532
1533
1534
1535
1536
1537
1538
1539
1540
1541
1542
1543
1544
1545
1546
1547
1548
1549
1550
1551
1552
1553
1554
1555
1556
1557
1558
1559
1560
1561
1562
1563
1564
1565
1566
1567
1568
1569
1570
1571
1572
1573
1574
1575
1576
1577
1578
1579
1580
1581
1582
1583
1584
1585
1586
1587
1588
1589
1590
1591
1592
1593
1594
1595
1596
1597
1598
1599
1600
1601
1602
1603
1604
1605
1606
1607
1608
1609
1610
1611
1612
1613
1614
1615
1616
1617
1618
1619
1620
1621
1622
1623
1624
1625
1626
1627
1628
1629
1630
1631
1632
1633
1634
1635
1636
1637
1638
1639
1640
1641
1642
1643
1644
1645
1646
1647
1648
1649
1650
1651
1652
1653
1654
1655
1656
1657
1658
1659
1660
1661
1662
1663
1664
1665
1666
1667
1668
1669
1670
1671
1672
1673
1674
1675
1676
1677
1678
1679
1680
1681
1682
1683
1684
1685
1686
1687
1688
1689
1690
1691
1692
1693
1694
1695
1696
1697
1698
1699
1700
1701
1702
1703
1704
1705
1706
1707
1708
1709
1710
1711
1712
1713
1714
1715
1716
1717
1718
1719
1720
1721
1722
1723
1724
1725
1726
1727
1728
1729
1730
1731
1732
1733
1734
1735
1736
1737
1738
1739
1740
1741
1742
1743
1744
1745
1746
1747
1748
1749
1750
1751
1752
1753
1754
1755
1756
1757
1758
1759
1760
1761
1762
1763
1764
1765
1766
1767
1768
1769
1770
1771
1772
1773
1774
1775
1776
1777
1778
1779
1780
1781
1782
1783
1784
1785
1786
1787
1788
1789
1790
1791
1792
1793
1794
1795
1796
1797
1798
1799
1800
1801
1802
1803
1804
1805
1806
1807
1808
1809
1810
1811
1812
1813
1814
1815
1816
1817
1818
1819
1820
1821
1822
1823
1824
1825
1826
1827
1828
1829
1830
1831
1832
1833
1834
1835
1836
1837
1838
1839
1840
1841
1842
1843
1844
1845
1846
1847
1848
1849
1850
1851
1852
1853
1854
1855
1856
1857
1858
1859
1860
1861
1862
1863
1864
1865
1866
1867
1868
1869
1870
1871
1872
1873
1874
1875
1876
1877
1878
1879
1880
1881
1882
1883
1884
1885
1886
1887
1888
1889
1890
1891
1892
1893
1894
1895
1896
1897
1898
1899
1900
1901
1902
1903
1904
1905
1906
1907
1908
1909
1910
1911
1912
1913
1914
1915
1916
1917
1918
1919
1920
1921
1922
1923
1924
1925
1926
1927
1928
1929
1930
1931
1932
1933
1934
1935
1936
1937
1938
1939
1940
1941
1942
1943
1944
1945
1946
1947
1948
1949
1950
1951
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040
2041
2042
2043
2044
2045
2046
2047
2048
2049
2050
2051
2052
2053
2054
2055
2056
2057
2058
2059
2060
2061
2062
2063
2064
2065
2066
2067
2068
2069
2070
2071
2072
2073
2074
2075
2076
2077
2078
2079
2080
2081
2082
2083
2084
2085
2086
2087
2088
2089
2090
2091
2092
2093
2094
2095
2096
2097
2098
2099
2100
2101
2102
2103
2104
2105
2106
2107
2108
2109
2110
2111
2112
2113
2114
2115
2116
2117
2118
2119
2120
2121
2122
2123
2124
2125
2126
2127
2128
2129
2130
2131
2132
2133
2134
2135
2136
2137
2138
2139
2140
2141
2142
2143
2144
2145
2146
2147
2148
2149
2150
2151
2152
2153
2154
2155
2156
2157
2158
2159
2160
2161
2162
2163
2164
2165
2166
2167
2168
2169
2170
2171
2172
2173
2174
2175
2176
2177
2178
2179
2180
2181
2182
2183
2184
2185
2186
2187
2188
2189
2190
2191
2192
2193
2194
2195
2196
2197
2198
2199
2200
2201
2202
2203
2204
2205
2206
2207
2208
2209
2210
2211
2212
2213
22

Docket No. BPHOTO.003

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, however, as well as a preferred mode of use, further objectives and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings, wherein:

10

Figure 1a shows side view of an innovative DBR laser.

Figure 1b shows a top view of an innovative DBR laser.

Figure 2a shows a side view of crossed DBR lasers.

Figure 2b shows a top view of crossed DBR lasers.

15 **Figure 2c** shows a close up of crossed outcoupling gratings.

Figure 3 shows a side view of a DBR laser with a reflective undercoating to reflect laser light.

20 **Figure 4a** shows a top view of a DBR with flared or tapering gain regions.

Figure 4b shows a top view of crossed DBRs each with flared or tapered gain regions.

Figure 5a shows a side view of a laser diode having a DBR at one end and a cleaved facet at the other end.

25 **Figure 5b** shows a top view of crossed lasers, using both DBRs and reflecting facets.

Figure 5c shows a top view of a laser diode using cleaved facets.

30 **Figure 6** shows a laser diode using cleaved facets and a reflective layer beneath part of the waveguide.

Docket No. BPHOTO.003

Figure 7a shows a top view of four crossed DBR lasers each outcoupling light from the same outcoupling element.

Figure 7b shows a close up of the crossed gratings for the laser system of **Figure 7a**.

5 **Figure 8** shows a circuit diagram of integrated elements with the presently disclosed laser system.

Figure 9 shows optical waveguides routing light from the laser to other elements.

10 **Figure 10** shows a possible configuration for integrated elements with a laser diode.

Figure 11 shows another possible configuration for integrating added elements to the present innovations.

Figure 12 shows another embodiment of the present application.

15 **Figure 13** shows another embodiment of the present application.

Figure 14 shows a DBR laser with thinned quantum wells beneath the outcoupling grating and beneath the DBRs.

20 **Figure 15** shows another embodiment of the present application.

Figure 16 shows a laser diode for implementation in a preferred embodiment.

25 **Figure 17** shows two laser cavities coupled together to output light through a common outcoupling aperture, according to a preferred embodiment.

Figure 18 shows a detail view of the outcoupling aperture of the innovative laser diode system.

Figure 19A shows a detail of the coupling region.

30 **Figure 19B** shows a detail of the coupling region with grating enhanced coupling.

Docket No. BPHOTO.003

Figure 20 shows how a multiplicity of cavities can be implemented as a preferred embodiment.

Figure 21 shows an alternate configuration of multiple
5 waveguides and cavities according to a preferred
embodiment.

Docket No. BPHOTO.003

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The numerous innovative teachings of the present application will be described with particular reference to
 5 the presently preferred embodiment (by way of example, and not of limitation).

First order outcoupling gratings and second order or higher outcoupling gratings are both used in at least some embodiments of the present innovations. In the present
 10 application, first order DBR refers to a distributed Bragg reflector grating that reflects light within the waveguide in first order for feedback. A second order DBR grating will outcouple light in first order, and feedback light in second order.

15 In several variations in this application, second order feedback gratings (which couple light out in first order) are used. In such arrangements, the feedback grating depth or strength is varied in the y and z directions so that both the loss and the feedback from the
 20 grating help to stabilize the laser mode. For example, the first order lateral mode will be stabilized if the grating strength is varied so that the feed back varies like a Gaussian. This is accomplished by forming the grating so that its strength varies as

25

$$1 - \exp[-(y/\omega)^2]$$

Docket No. BPHOTO.003

where y is the direction parallel with the feedback grating surface and perpendicular to the cavity length, with the origin taken to be at the center of the out-coupling grating, and ω is half the y grating dimension.

First order outcoupling gratings are gratings which couple light out of the waveguide plane in first order but may or may not satisfy the in-plane Bragg condition for second or higher order Bragg reflection. Such gratings may be designed to create no second or higher order reflections which feedback into the laser mode. In these variations which use such out-coupling gratings with no in-plane feedback, the gratings cause no destabilizing feedback into the laser mode and are mechanically and electrically isolated from the structure used to form and pump the resonant laser cavity. Thus, the length and position of the output grating can be chosen to suit the needs of the application for which the laser is designed. The grating periods required for outcoupling, with and without in-plane reflections, are summarized in "Surface Emitting Semiconductor Lasers and Arrays," G.A. Evans and J.M. Hammer, Eds., Academic Press, 1993, which is hereby incorporated by reference.

In general, second and higher order feedback gratings can result in some outcoupling. However, these are less preferred in the context of the present application since such higher order interactions are less efficient.

The outcoupling angle of the gratings in the innovative systems herein disclosed is measured as an angle from the normal to the surface of the outcoupling

Docket No. BPHOTO.003

grating. Resonant outcoupling occurs when the outcoupling grating has a period that is equal to an integer number of wavelengths of the light in the cavity. A grating with period equal to the wavelength of light in the laser cavity will outcouple some light normal to the laser plane and reflect some light in-plane in second order. This means the light exits the grating parallel or nearly parallel to the normal. Outcoupling of light off the normal occurs when the grating is not an integer number of guide wavelengths, and in such a case the light exits the grating at an angle from the normal. This angle depends on the difference between the guide wavelength and the grating period. Varying the wavelength of light or the outcoupling grating period can therefore have great effect on the angle of outcoupled light. The out-coupling grating length, longitudinal position, and the output angles may therefore be chosen over a large range of values. The grating may also be shaped to achieve an output beam of a desired cross section. This is valuable for coupling the output light into fibers of different cross sectional size or at different angles than exactly or nearly normal. All of these "off normal" parameters may be varied without fear of significant mode destabilization or disruption of laser coherence. In the case of exactly or near normal outcoupling, there can be significant in-plane reflection that may (or may not) adversely affect the performance of the laser.

Figure 1a shows a cross sectional view of a preferred embodiment, taken to show the x-z plane. It should be understood that the features in the several figures may

Docket No. BPHOTO.003

not be to exact scale because of the large differences in dimension between the various structures illustrated.

Layers 3, 4, 5, and 6 are grown on a substrate 2 by known means. Each of these layers may comprise a number of sub-layers. Beneath the substrate is the n contact layer 14. The substrate may comprise a thick layer of n-type semiconductor with a top layer of similar n-type material interposed beneath layer 3. This is frequently called the n-cladding or n-clad. The n-clad will have a refractive index below that of layer 3. Layer 3 is the active and guiding layer usually containing the junction between p- and n-type semiconductor materials. It may comprise, for example, a sequence of one or more barrier layers alternating with quantum well layers. Layer 4 is a p-type clad layer and has lower refractive index than layer 3. Layer 5 may be a multi-layer including a p-clad material chosen to enable good contact to 6 which is the p-metallic contact. Layer 14 provides the other electrical contact for the laser. There are many sequences of possible layers for semiconductor lasers and amplifiers, and the present innovations are not limited to the structures recited here. For example, a structure with a p-type rather than an n-type substrate (and all the necessary alterations to accommodate a change from p- to n-type materials and vice versa) is within the contemplation of the present application.

Gratings 7 are surface relief DBR gratings chosen to reflect light in the +/-z direction to form the laser cavity. (Note that these gratings can be buried structures within the device, and the term "surface relief" does not

Docket No. BPHOTO.003

require the grating be on the surface of the device after processing.) The laser mode will be a standing wave which may be considered to be formed by two waves one flowing in the +z direction, the other in the -z direction. First
5 order DBR gratings are preferred, but second or higher order gratings are also possible. The DBR grating depth and length and the thickness of layer 4 are chosen to provide the desired feedback as known in the art.

The reflector gratings can be given added
10 functionality by varying their grating strength or amplitude in both the y (lateral) direction and the z (cavity) direction. Variation of the grating strength in the lateral direction will impart to the cavity mode light a Gaussian shape, allowing for more of the optical energy
15 of the emitted light to be coupled into a circular mode, such as a fiber. Variation of the grating strength in the z direction can improve the suppression of unwanted longitudinal modes on either side of the desired longitudinal mode. the degree to which the unwanted modes
20 are suppressed is called the side-mode suppression ratio.

The outcoupling grating 8 (sometimes referred to herein as OC grating, or OCG) is a surface relief grating with period chosen to couple light at desired angles from the grating plane. It is located at an aperture on the
25 surface of the device. In a preferred embodiment, the outcoupling gratings are about 10 microns wide. The outcoupling grating may be shaped to control the shape of the emitted beam. The grating depth and thickness of the p-clad layer 9 in the vicinity of the grating 8 are chosen
30 to provide the desired degree of outcoupling and to

Docket No. BPHOTO.003

control beam shape. A window or aperture 10 in layers 5 and 6 is provided to allow unobstructed emission of light, and the size and shape of the outcoupling grating is matched to the mode of the fiber to which it couples light (in one embodiment). Because of the two standing waves in the cavity and reflection from the grating, the outcoupling grating simultaneously emits four different light beams, two above and two below the grating plane. These are depicted by dashed arrows. In the case of normal outcoupling of the laser light, the two top lobes are combined into a single beam, as are the two bottom lobes of emitted light.

In one embodiment, the outcoupled light is emitted normal to the surface, since one primary goal is to couple this light into a fiber. When light is emitted normal to the surface, the two top emitted beams are combined into a single beam, and likewise with the downward emitted beams.

Off normal emissions and slightly off normal emissions are also very useful. For example, changing the angle of entry to a fiber by several degrees has minimal impact on the coupling efficiency yet allows the use of an off resonance grating which minimizes undesired feedback into the laser. A larger angle might be desirable to send light to another detector to monitor the laser.

Figure 1b shows a top view of a single grating outcoupled DBR laser. The outcoupling grating 8 is located at an outcoupling aperture within the envelop of the gain region. On either end of the laser are located distributed Bragg reflectors 7 for providing feedback into the cavity. Of course, cleaved facets may also be used instead of

Docket No. BPHOTO.003

reflector gratings, with highly reflective coatings applied to reflect the light, as shown in later embodiments. With either DBR reflectors or coated facets, the reflectivity of one or both ends can be varied to
5 allow light to escape the cavity for other purposes.

Another embodiment will be discussed with reference to **Figures 2a and 2b**. In this variation, crossed out-coupling gratings are located within the cavities of two (or more) semiconductor lasers arranged at angles to one
10 another and located on a common substrate. In one embodiment, two lasers are used and are positioned at 90 degrees from one another, but more lasers are of course possible--see **Figure 7a** for example. The shape and strength of the two gratings are chosen to produce
15 desirable properties in the out-coupled light. Their periods are individually chosen to suit the desired application, such as to control outcoupling angle, or to couple out different wavelengths.

Figure 2a shows a side view of the crossed grating outcoupled DBR lasers. The structure when seen from the
20 side is similar to that of **Figure 1**. Elements that are unique to the laser running in the z-direction are labeled with a z suffix, and elements unique to the laser running in the y-direction are labeled with a y suffix.

Referring to **Figure 2b**, a top view, two crossed DBR lasers are at 90 degrees to one another. Each laser has its own set of reflector gratings 7y, 7z at either end, and both lasers have their own out-coupling grating 8y, 8z positioned at a common location between the reflector
30 gratings. (In the preferred embodiment, the outcoupling

Docket No. BPHOTO.003

aperture is located at the center of the laser, but this is not necessary.) On either side of the out-coupling gratings are the pumped regions of the lasers. (Note that in this variation, the two gain regions of a single laser are discontinuous, having different parts on either side of the outcoupling grating. Other possible embodiments include a single gain region with an outcoupling grating outside the gain region but between the reflector gratings, or even a single continuous gain region that spans the outcoupling grating, having portions on both sides.) The two out-coupling gratings are located at the same place, and the superposition of the two gratings forms a virtual grating with an effective period at an angle of about 45 degrees if the grating periods are about the same for each laser.

The reflector grating periods are chosen to internally reflect the proper wavelength of light. The reflectivity of the DBR is very high at the Bragg condition, and drops off rapidly when the wavelength is different than the Bragg condition wavelength. This allows the wavelength of the output light to be controlled by controlling the period of the DBR gratings.

Referring again to **Figure 2a**, in the case of crossed lasers, a cross section taken parallel to the x-y plane would be similar with layers noted with y subscripts in place of z subscripts.

Gratings $8y$ and $8z$ are surface relief outcoupling gratings with periods chosen to couple light at desired angles relative to the grating (y-z) plane. As shown in the figure, the gratings can be shaped to control the

Docket No. BPHOTO.003

profile of the outcoupled beam. A circular profile for the grating is indicated (a more complicated profile would be optimal for fiber coupling), but any other useful shape can be produced, depending on the application. The grating
5 depth along with the thicknesses and compositions of the epitaxial structure of the laser are chosen to provide the desired degree of out-coupling.

For each laser, four beams are emitted because of the left and right running waves that form the standing wave
10 mode of the laser (unless the light is outcoupled perpendicular to the device). Two beams symmetrically angled around the normal will emerge above the grating plane and pass through the window 10. Similarly, two beams will be directed towards the substrate below. (Note the
15 epi layers are transparent and this transparency can be made use of to couple light out through the bottom of the device. In such a case, a reflector is placed on the top of the device to direct the top emitted light back into the laser or out the bottom.) In some designs, the grating
20 may be blazed to allow light to be outcoupled to the right or left of normal as well.

When two or more lasers are combined in this way, the crossed outcoupling gratings each polarize the light which they outcouple. In the case of two crossed gratings at 90
25 degrees, the two beams of light will be polarized at 90 degrees with respect to one another. Coupling light into a fiber with two orthogonal polarizations is required for pumping Raman amplifiers.

Figure 2c shows a close up of the outcoupling
30 gratings of **Figures 2a and 2b**. The periods, **L_y** and **L_z** , of

Docket No. BPHOTO.003

the superimposed two gratings need not be identical. The OCG periods will depend both on the wavelength of light in the cavity (which in turn depends on the periods of the DBR gratings at either end of the cavity) and on the
5 desired outcoupling angle for the emitted beam. By choosing the two gratings to have different OC angles, spatial separation is possible, as may be desired by particular applications. In still another embodiment, the laser light from the devices is emitted normal to the
10 surface, so that both wavelengths of light can be coupled into a fiber through the same aperture or location on the device.

By choosing a non-resonant spacing for the outcoupling grating period (i.e., a distance between
15 grating lines that is not an integer multiple of the wavelength of light within the cavity) the output beams are emitted non-normal to the surface. This is useful in applications where, for example, the fiber into which the light is to be coupled is at an angle relative to the out-
20 coupling grating.

The choice of normal or off normal outcoupling angles can have other advantages. For example, when two or more different wavelengths of light are coupled out of the OC gratings, all wavelengths can be coupled into the same
25 fiber or separated as desired by varying the output angles of the individual gratings. For example, the individual outcoupling gratings for two crossed devices could each couple different wavelengths of light out normal to the surface to couple two different wavelengths into a single
30 fiber mode. This is particularly applicable in the crossed

Docket No. BPHOTO.003

grating out-coupled lasers, discussed further below. If, for some reason, only one wavelength is needed in the fiber, the light from the other device can be emitted off normal so as to not couple into the fiber. The non fiber
5 coupled light could be deflected to a detector, for example. Regardless of the particular use, the choice of outcoupling angles is an advantage to a laser device, and the present application shows how different wavelengths from different sources can be selectively combined into a
10 single region for coupling, or separated into different regions.

The shape and strength (i.e., the depth) of the OC gratings are chosen to produce desirable properties in the out-coupled light. The periods of all OC gratings can be
15 individually chosen according to the needs of that particular laser and the application. For example, the two crossed OC gratings of **Figure 2b** can be chosen to outcouple different wavelengths of light, allowing the two lasers of the crossed laser configuration to have
20 different wavelengths, one in the z-direction, another in the y-direction. This of course extrapolates to higher numbers of lasers. Additionally, the two outcoupling gratings (and the different laser diodes themselves) can be chosen to emit the same wavelengths (for example, by
25 making their feedback grating periods the same) allowing additional power and polarization variety in the outcoupled beam(s).

The basic idea can be extended to include a multiplicity of lasers radially arranged around a set of
30 gratings oriented to outcouple light independently for

Docket No. BPHOTO.003

each laser. This allows many wavelengths of light to be generated by merely choosing a different period for the pair of DBRs for each individual laser. The OC gratings can couple this light into a single spatial region (for example, to couple several wavelengths of light into a fiber for DWDM applications), or it can couple the different wavelengths out of the devices at different angles.

Referring still to **Figure 2b**, which shows crossed lasers according to a preferred embodiment, if the Bragg reflector gratings are chosen to have the same period in both the y-direction laser and the z-direction laser so that both lasers operate at the same wavelength, and if the crossed OC grating period L_z is the same as L_y , the superposition of the two gratings at right angles results in a virtual grating with an effective period angle of about 45 degrees (if both grating periods are the same). In this case the possible coupling between the y and z lasers can be avoided if the gain regions use quantum wells with compressive strain and thus favor TE mode operation. The virtual grating at 45 degrees will not efficiently reflect TE modes and therefore will not couple the y and z lasers. On the other hand, the use of tensile strain in the quantum well favors TM modes, and may result in enough coupling to either lock the y and z lasers together into a single coherent source, or provide significant cross-talk and other interactions between the two lasers. Thus, the disclosed approach can choose the nature of the output beams to be either a combined single frequency coherent source, or two output beams with two

Docket No. BPHOTO.003

independent wavelengths, or two beams with independent wavelengths but with a controlled amount of crosstalk between them.

The reflector grating periods for the pair of lasers
5 can be the same, which provides additional power and polarization variety. Alternatively, the grating periods can be different, resulting in two different wavelengths of light being outcoupled. This latter configuration can couple light of different wavelengths out at the same
10 angle for coupling light of different wavelengths into the same fiber, saving the cost of implementing a combiner for this function. For example, if the two lasers have different feedback grating periods, they will each generate a different wavelength of light. But both lasers
15 can emit their light normal to the surface of their respective outcoupling grating by choosing each individual outcoupling grating to couple the necessary wavelength of light out normal to the surface.

The size of the grating output aperture can be
20 adjusted for optimum coupling to single or to multi-mode fiber. Likewise, the efficiency of the output element (be it a grating or other element, such as a beam splitter or holographic optical element) can be adjusted by adding a layer of dielectric material to the outcoupling region. If
25 outcoupling efficiency is too high, a high threshold current is required to lase because of the quantity of photons escaping the cavity. With a reflective layer atop the outcoupling grating, some of the light is reflected and continues to oscillate within the cavity. This has the
30 effect of marginally decreasing the required current for

Docket No. BPHOTO.003

lasing. Adding a dielectric layer (for example, nitride, or a dielectric stack, or even a reflective metallic layer) to the outcoupling location therefore controls outcoupling loss and decreases the required threshold
5 current.

In any configuration of the present application where one or more gratings are located and superimposed on one another, the separate gratings can be individually formed by conventional means (including multiple exposures and
10 etches to form the pattern) or can be merged into a single element using a holographic optical element (HOE). The optical requirements of the gratings can be calculated, and a HOE can be designed that accomplishes these required optical functions. Once designed, such a HOE can be
15 patterned for lithography, and can therefore be fabricated in fewer process steps than it would take to create the multiple gratings separately. For example, multiple divergent beams can be captured and coupled into a single fiber with HOEs.

In another embodiment, shown in **Figure 3**, a reflecting surface is placed beneath the outcoupling gratings. This surface **11** reflects the two lower lobes of emitted light. This reflective layer can be made from a metallic substance or other material reflective to the
20 necessary wavelengths of light, or it might be a reflective grating formed in the device, for example. By coupling the lower lobes back up and out of the OC grating, greater power is coupled out of the laser and may
25 be captured by a fiber or other device, such as a detector
30 to monitor the light produced by the device. A space **12** is

Docket No. BPHOTO.003

shown in the substrate of the figure, but the same reflective surface can be placed with the substrate intact.

Another embodiment is shown in **Figure 4a**, which shows
5 a method to increase the lateral width of the gain regions at the outcoupling grating while maintaining a single-transverse mode. This is accomplished by using a single mode waveguide in the gain region that connects to a tapered gain region. The taper angle is related to the
10 divergence of the fundamental mode of the single mode waveguide. In the preferred embodiment, the tapered regions have a laterally varying current contact, such as a gaussian contact to stabilize the modes in the tapered device.

15 The embodiment shown in **Figure 4a** has a tapered gain region **13**. The gain region in this sample has a straight portion as well. Different contacts are used in the preferred embodiment, pumping the different regions with increasing current as necessary. The tapered gain region
20 ensures a wide-spatially-coherent mode, and avoids the restriction on the lateral (y) dimension imposed by the requirement of single lateral mode operation. A wide lateral mode allows the width of the output beam to be set by the width of the grating. The grating area can take a
25 desired shape to match the needs of various applications. For example, circular, elliptical, or Gaussian beams can be produced.

Figure 4b shows the tapered gain regions used with multiple crossed grating outcoupled lasers. This
30 embodiment shows two crossed GO (grating outcoupled)

Docket No. BPHOTO.003

lasers at 90 degrees to one another. DBR gratings 7y, 7z, create the cavity as in other embodiments discussed above. The pumped regions of the lasers in this variation have a flared section (labeled with the **f** suffix), being wider
5 closer to the OC gratings. In this example, one laser has an outcoupling grating that is circular in shape, while the other laser has an outcoupling grating that is rectangular. Using a tapered gain region, outcoupled beams of a greater range of sizes can be produced, as the gain
10 region can be made to whatever width is necessary to accommodate (or fully take advantage of) the size of the OC grating. Tapered gain regions also increase the total amount of emitted power from the device.

Another embodiment is shown in **Figure 5a**. At one end
15 of the laser, the DBR has been replaced by a reflective end facet **7y**. There are still two gain region portions, separated by the OC grating in this embodiment. The other end of the laser has a DBR **7yB**, the period of which determines the wavelength that will be stable in the
20 cavity.

A top view of a crossed GO laser system is shown in **Figure 5b**. In this variation, the laser running in the z-direction (horizontal in the figure) has reflective end facets on both ends, and no DBRs for reflecting the light
25 in the cavity. The y-direction laser (vertical in the figure) has a DBR at one end, and a reflective facet at the other end. Cleaved facet ends reduce the length of the device since the length of the DBR sections is omitted.

Figure 5c shows a top view of a laser diode with
30 cleaved facets at both ends. The length of the gain region

Docket No. BPHOTO.003

is fixed by the reflectivity of the end facets or the DBRs.

Figure 6 shows a laser with two reflective end facets and an OC grating between the pumped regions. Beneath the
5 OC grating is a reflector for reflecting the two downward directed beams back up toward the surface of the laser. Capturing the downward beams is useful to increase efficiency.

Figure 7a shows a GO laser system with four crossed
10 lasers being outcoupled at the same spatial location. Distributed Bragg reflectors are shown in this example at each end of the individual lasers. Each laser has its own OC grating superimposed on the other OC gratings to create one virtual grating. (Note that it is possible to overlap
15 the gratings in different planes, having either curved waveguides or making each laser totally in a different plane than the others, but this is a less preferred embodiment. HOEs can be used in place of multiple gratings in such a situation.) **Figure 7b** shows a close-up of the
20 outcoupling gratings for the four laser system. There are four gratings, each at a 45 degree angle to the adjacent gratings. The periods of these gratings need not be the same, which allows the use of multiple wavelengths being outcoupled at the same location (assuming the lasers
25 themselves are fashioned to output different wavelengths). The periods of the various gratings are labeled as L_z , L_y , L_{zy} , and L_{yz} .

The structure of the grating outcoupled laser allows
for the high-level integration of electronic circuitry
30 with the laser device. Many different possible devices can

Docket No. BPHOTO.003

be integrated with the GO laser of the present application, including control electronics and photonic integrated circuits that can be placed on the chip with the laser; electronic integration includes higher level
5 data management electronics such as serialization/deserialization, clock generation and recovery, op amps and analog-to-digital and digital-to-analog converters. The GO laser geometry is also advantageous in that it allows for integration with
10 optical waveguides and integration of light routing circuitry on the chip. Such photonic integration allows optical interconnects between circuit elements, integration of optical isolators, wavelength tunable sections, optical modulators, waveguide couplers,
15 waveguide switches, and simultaneous integration of multiple ones of these components.

Figure 8 shows an example of a higher level circuit integration on the same chip as the grating outcoupled laser diode. In this example, laser driver and control
20 electronics are integrated. Din and Din-bar are differential data inputs and EN is the chip enable. Internal logic and BIAS control is used to center the data to the inputs of the driver pair and to provide a Vref output. This output is used with Rset to control the
25 current source or modulation current I_{mod} which sets the output current to the grating outcoupled laser diode. The resistor R_{ext} is external to minimize the power dissipation capacity, both R_{ext} and R_{set} may be integrated as well.

Docket No. BPHOTO.003

Figure 9 shows the optical waveguide technology routing the light from the laser source to another integrated circuit component, for example. One end of the laser has a partially transmitting reflector **902** which
5 allows some of the light to pass through. This light is guided by a waveguide **904** to another circuit element as desired for any given application. In the example shown, a corner turning mirror **906** is used to guide the light.

Other devices can also be integrated on the same chip
10 with the innovative laser system of the present application. **Figure 10** shows a grating outcoupled laser diode with the OCG **8** between the two reflectors **902** at either end of the cavity. One or both reflectors are partially transmitting gratings in this example. In this
15 variation, a waveguide coupler, which may be used for connecting to other integrated devices, is located outside the laser cavity. A location for such an integrated device **1002** is shown at either end of the cavity. Of course, other devices could also be integrated, for example,
20 modulators or tuning sections.

Figure 11 shows another possible variation for integrating added components (such as a phase adjustor, for example). In this example, two regions **1002** where added devices may be fabricated on chip are shown. In this
25 example, the added components are located within the length of the laser, possibly requiring the gain region contacts to be moved or altered to accommodate the added device.

Figure 12 shows another embodiment of the present
30 innovations. In this variation, a reflective coating **1202**

Docket No. BPHOTO.003

(for example, a dielectric stack or a metal layer) is placed on top of the device, where the outcoupling grating 1204 is located. This reflective coating causes the light to be coupled through the bottom of the device. (Note that
5 it is often useful to allow some light to escape the top of the device in this design, as this light can be used to allow easier wafer level probe testing of the device.) If an outcoupling grating is used without such a reflective coating, there is of course light emitted both above and
10 below the waveguide due to reflection from the grating. The reflective coating causes the top emitted lobe of light to instead be emitted through the bottom of the device, so that substantially all light emitted from the cavity is coupled out through the substrate material,
15 which is a transparent material, usually about 100 microns thick. The reflective coating can be metallic (such as gold) or it can be a dielectric stack for better reflection. Generally, if the light is to be emitted out the bottom of the device, a high reflect (HR) coating is
20 placed on top of the device to reflect the light downward. An anti-reflect (AR) coating may be added to the bottom of the device in this case. Alternatively, if the light is to be emitted out the top surface, the HR coating may be placed on the bottom of the device, and an AR coating
25 placed on top.

Causing the light to be emitted through the bottom of the device has the advantage of allowing the heat sink to be placed on the top of the laser, closer to the locations where heat is generated, increasing efficiency of heat
30 sinking. In such a case, the device is preferably mounted

Docket No. BPHOTO.003

"upside down", with the reflective coating and DBRs beneath, the substrate on top, facing a fiber core for coupling, for example. This variation helps feedback in the cavity and can decrease threshold current by 50% or more.

In **Figure 12**, the laser device is shown with an outcoupling aperture between the DBRs. An outcoupling grating is shown in this example. On top of this grating is located a reflective coating that directs outcoupled light down through the substrate.

The gain region or regions of the present innovations can be modified to provide added functionality. **Figure 13** shows a DBR laser according to an embodiment of the present innovations. The gain region **1300** has multiple parts in this example, one on either side of an outcoupling grating. One part of the gain region is further split into two parts, a larger **1302** and a smaller **1304** section. The smaller part, which can be used to more sensitively adjust the current supplied to the gain region, is used for several purposes. It can be used as a fine tuning device for the wavelength of the light in the cavity. By increasing or decreasing the current, the wavelength can be slightly tuned to some degree. The smaller contact can also be used to modulate the signal generated in the cavity. By varying the supplied current over time, the intensity of the emitted light can be varied. This can be used to modulate the signal by adjusting the current over time to alter the intensity of light, and thus embed a signal in the emitted light. The smaller contact is the preferred one to use for such

Docket No. BPHOTO.003

modulation, since it will allow faster modulation (due to lower capacitance, etc.).

Figure 14 shows a side view of a DBR laser according to another embodiment. The laser has a cavity and two reflector gratings 7, one at each end. Between the reflector gratings are the gain region **1402** and the outcoupling grating 8.

The waveguide 3 in the laser may be made from multiple layers including an active and guiding layer containing the junction between the p and n type semiconductor materials. For example, this region might comprise a sequence of one or more barrier layers alternating with quantum well layers.

In the embodiment shown in the figure, the quantum wells **1404** are made thinner beneath the reflector gratings 7 and beneath the outcoupling grating 8. This results in a less lossy, more transparent device. The larger bandgap in the thinner quantum well regions (i.e., in the unpumped regions) means less absorption of photons in the cavity because higher photon transition energy is required. This lowers internal loss, increases efficiency, and lowers the required threshold current for the device.

The quantum well thickness, by controlling the required transition energy, affects the wavelength of the photons that will lase in the cavity. This allows large scale tunability of the device during fabrication by controlling quantum well formation.

Quantum wells are fabricated at different thicknesses using selective growth of epitaxial layers. This selective growth phase of processing can also be used to

Docket No. BPHOTO.003

simultaneously improve the performance of integrated components such as electro-absorption modulators, which benefit from quantum well structures that can be made more transparent (or have a higher photon transition energy).

- 5 The integrated devices are fabricated at the same time and during the same set of processes as the lasers themselves, and selective growth can be used on them without significant process cost added.

Figure 15 shows another embodiment. In this variation, a fractional-spherical lens **1502** made of an optical polymer is formed on the outcoupling grating **1504** (by a microjet process, for example). This lens acts to make different wavelengths of light (which may exit the OCG at different angles than the normal, or from one another) converge to be coupled into a fiber mode, for example. Since the index of refraction of the material outside the lens is lower than the index of refraction of the lens, light rays passing through the lens to the lower index material will be refracted away from the normal to the surface of the lens at that point. Depending on the index difference, the refraction can be great or small. This element can be used to allow design margin in the size of the outcoupling grating. With the added lens, the outcoupling grating can be made larger, (50 microns, for example), which is useful in high power applications. Normally, an outcoupling grating of 10 micron size can outcouple light in the hundreds of milliwatt range or higher, but with larger outcoupling gratings light of higher power, well above a watt, can be outcoupled and confined to a fiber mode.

Docket No. BPHOTO.003

Other types of intermediate lens devices (gratings, HOEs, etc.) can also be used at this location to aid in coupling light from the outcoupling grating into a fiber core (for example). Such devices can be made on chip, or
5 be separate devices added after processing is complete.

Figure 15 shows a sample embodiment of the device. This embodiment comprises a DBR laser as described previously in this application, with outcoupling grating 1504 located between the two reflector gratings 1506. Gain
10 regions 1508 are on either side of the OCG. A lens 1502 which is partly spherical in shape is formed on the outcoupling grating.

Figure 16 shows a top view of a surface emitting laser diode (LD). The LD comprises reflectors, preferably distributed Bragg reflectors (DBRs) 1602, at either end of
15 a waveguide 1604. Contacts 1606 are positioned between the DBRs for electrically pumping the active or gain region. An outcoupling element 1608 is positioned within the envelope of the pumped region in this example. Note that
20 the outcoupling element could also be at one end of the pumped region, between the two reflectors 1602. In the preferred embodiment, the outcoupling element is a Bragg grating or a holographic optical element (HOE). The active region is excited by current applied to the electrodes,
25 causing stimulated emission of photons in the waveguide. This light is reflected within the cavity by the two DBRs positioned at either end. The period of these DBRs determines which wavelengths will satisfy the Bragg condition, and therefore which wavelengths will resonate
30 within the cavity. This light is coupled out of the

Docket No. BPHOTO.003

5 waveguide at an angle to the surface of the waveguide by the outcoupling grating (OCG). The outcoupled light will be emitted normal to the surface if the OCG has a period equal to an integer number of wavelengths of the light resonating in the cavity. If the period is not such an integer number of wavelengths, then the light is emitted at an angle to the normal. This device is referred to in the present application as a grating outcoupled (GO) laser, and forms the central waveguide referred to below.

10 (The waveguides disclosed herein can be ridge guides, buried heterostructures, or any other waveguide technology.)

Figure 17 shows a GO laser with laterally coupled waveguides. The structure comprises a GO laser as in Figure 16 with waveguides 1710 (referred to as waveguides +1) attached to the central waveguide 1712 (referred to as waveguide 0) as shown. The added waveguides 1710 are attached to both sides of the central waveguide 1712, forming a preferably symmetric structure. Each added waveguide 1710 has a reflector, preferably a DBR 1702, at the end to reflect light of a particular wavelength in the cavity. The added waveguides 1710 include contacts 1704 to electrically stimulate the active regions therein, causing electron hole recombination which gives off photons.

25 All the waveguides in the preferred embodiment have electrically pumped regions along much of the length of the waveguide structure. The pumped region can be limited to certain regions of the waveguide, but this would decrease power output. As shown in Figure 17, the waveguide +1 1710 couples to waveguide 0 1712 very near

30

Docket No. BPHOTO.003

the outcoupling grating 1708. This coupling can occur anywhere along waveguide 0 1712 between the DBR of waveguide 0 1712 and the OCG 1708. In an alternative embodiment, the added waveguides are passive, having no
5 pumped regions.

The electrical contacts used to pump the gain region have a tendency to alter the index of refraction in the waveguide due to gain induced index suppression. This provides another advantage to the present innovations in
10 that the contact located near the coupling regions 206 can be separate from the main contact 204. This allows the main contact to be pumped to obtain maximum power output, while allowing the contact in the coupling region to be pumped so as to maximize coupling efficiency between the
15 two waveguides.

For the structure shown in **Figure 17**, the added waveguides 1710 effectively add one resonating cavity to the laser diode system. Thus, light of central wavelength L_0 resonates within the central cavity (formed by
20 waveguide 0) because the DBRs at either end of the central cavity (i.e., waveguide 0) have periods chosen to satisfy the Bragg condition for wavelength L_0 . The DBRs at the ends of the second cavity (formed by waveguide +1) are chosen to satisfy the Bragg condition for wavelength L_1 .
25 Thus, light with central wavelength L_1 resonates within this cavity. Photons of wavelengths L_1 satisfy the Bragg condition and are reflected by the DBRs of waveguide +1. This sets up a standing wave for this wavelength in this cavity. The cavity for wavelength L_1 comprises both added
30 waveguides +1 on either side of the OCG, as well as the

Docket No. BPHOTO.003

part of waveguide 0 near and between the coupling region. Light resonating in waveguide +1 reflects off one DBR, couples to waveguide 0, goes past the OCG (at which light is output), then couples back into the other half of
5 waveguide +1, reflects off that side's DBR, and repeats the process.

The light from this added waveguide 1710 and from the central waveguide 1712 is output by the OCG 1708 at the center of the gain region in this figure. The period of
10 the OCG determines the outcoupling angle of the light. If the period is an integer number of wavelengths of the output light, the light is output normal to the surface. This is referred to as resonant outcoupling. Since each of
15 the two cavities resonates with light of a different wavelength, the light from each cavity will be output at different angles. In a preferred embodiment, the OCG has a period that outcouples light from the central cavity normal to the surface, and outcouples light from the
20 secondary cavity at an angle to the normal in what is called off-resonant outcoupling.

In a further innovation, an added optical element combines the various outcoupled beams so they may be coupled to (for example) a fiber core. Such a system is shown in **Figure 18**, which shows a close up view of the OCG
25 1804, seen from a side view. This figure shows the contacts 1802 for the gain regions on either side of the OCG 1804. The different wavelength beams (i.e., beam 0 and beam 1) emerge from OCG 1804 at different angles. Beam 0 emerges at the normal to the surface (indicating resonant
30 outcoupling for that wavelength), while beam 1 emerges at

Docket No. BPHOTO.003

an angle (indicating off-resonance outcoupling). Note there are two lobes to beams 0 and 1 because of the forward and rearward propagating waves in the cavities. The two lobes of beam 0 are atop one another because the
5 exit angle is the normal.

These different beams are preferably captured by another optical element 1806 which is positioned and fashioned to combine these spatially different beams into the same spatial region. In a preferred embodiment, the
10 outcoupling grating 1804 and the added optical element 1806 are fabricated directly on the chip as a holographic optical element. Note that in the figure the OCG 1804 and the added optical element 1806 are shown separate, but they may be placed contiguous with one another or even be
15 fashioned into the same element. Another alternative way to couple the light into a waveguide (such as a fiber) is to integrate a lens over the grating to collimate or focus beams of light into, for example, a fiber core. Such a lens is shown in Figure 15 as part of the outcoupling
20 grating in a laser diode.

Figures 19A and 19B shows details of the coupling region between the two waveguides 1902, 1904. In one embodiment (Figure 19A) the two waveguides 1902, 1904 are coupled only by evanescent coupling. Wavelength L1 couples
25 from waveguide +1 1904 into waveguide 0 1902. This results in both wavelengths L0 and L1 in waveguide 0 1902.

In another embodiment, the added waveguides 1904 are coupled to the central waveguide 1902 through grating 1906 assisted directional coupling. Such a system is shown in
30 Figure 19B. The two waveguides are brought close together

Docket No. BPHOTO.003

near the coupling point, allowing grating assisted coupling to occur. Since the two waveguides may be made from material with similar or identical indices of refraction, the evanescent coupling efficiency can be quite high and can suffice without the assistance of a grating. However, the use of a grating 1906 can make coupling even more efficient, or allow different index materials or different waveguide dimensions to be used for the two waveguides if necessary. Grating assisted coupling can also shorten the necessary interface between the two waveguides. Where a typical coupling relying solely on evanescent coupling might need hundreds to thousands of micrometers to obtain good coupling, use of a grating to assist coupling can reduce this distance greatly. In a preferred embodiment, the two waveguides 1902, 1904 are brought together, preferably at a distance of between 4-10 micrometers center to center. The exact figure of course depends on the dimensions and requirements of the laser diode system itself. A grating 1906 is positioned between the two waveguides to facilitate coupling. The grating is preferably fabricated as part of the semiconductor fabrication process.

The region where coupling occurs has, in a preferred embodiment, an electrical contact positioned to vary the optical properties of the waveguide to which it is connected. This contact can be either on the central waveguide, the lateral waveguide, or both. By varying the optical properties of either or both waveguides in this region, the amount of coupling between the waveguides is controlled. This coupling-controlling contact is

Docket No. BPHOTO.003

preferably separate from the contacts used to pump the gain regions of the waveguides.

Either contact can be used to modulate the light from the various waveguides. For example, in the case of a central cavity and a lateral cavity comprising two separate waveguides (as shown in **Figure 17**), the voltage applied to the contact in the gain region **1704** can be varied so as to vary the intensity of light generated in the lateral cavity. This intensity variation can be used to modulate the light out of the second cavity independently of modulation of the light from the first cavity. Likewise, the contact to the lateral waveguide which is located in the coupling region **1706** can also be used to modulate the light signal from the second cavity. This is done by varying the coupling percentage from the second cavity into the central cavity, and hence varying the intensity of the light from the second cavity output through the outcoupling aperture. Alternatively, both electrical contacts can be used at once to modulate the signal.

Figure 20 shows an extended version of the system, with multiple added waveguides attached to couple light ultimately into the central waveguide **0 2002**, so that the light from the multiple waveguides can be coupled out of the device by a single OCG **2010**. In this example system, N waveguides are added to each side of the central waveguide **0 2002**, with one side being numbered positive (waveguides $+1, +2, +3, \dots +N$) and the other side being numbered negative (waveguides $-1, -2, -3, \dots -N$). Each waveguide preferably has different DBRs **2008** at the ends, so that

Docket No. BPHOTO.003

each waveguide resonates with a different wavelength. Such a system is capable therefore of generating $2N+1$ distinct wavelength signals and coupling those signals from a single OCG 2010. The exact configuration shown in **Figure** 5 20 is an example, and other configurations are of course possible. For instance, the waveguides might be arranged differently to conserve area, by facing them in alternating directions as more waveguides are added.

Figure 21 shows another possible configuration of 10 cascaded or nested waveguides to form a plurality of cavities in the laser diode system. In this example, a laser diode 2102 has an outcoupling aperture 2104 positioned to emit light from various laser cavities. the central cavity 2106 is positioned with other waveguides 15 2108, 2110, 2112 fabricated nearby, with part of the other waveguides 2108, 2110, 2112 positioned very near to the central waveguide 2106. Switches, preferably comprising electrical contacts which can vary the optical properties of selected waveguides, are also shown at the coupling 20 regions for each waveguide. This configuration has the advantage of not requiring light of different wavelengths to pass through a multiplicity of coupling regions, each of which may be designed for coupling only a particular wavelength of light.

25 It should also be noted that the various laser diodes can be operated at different wavelengths, or selected ones can be formed to operate at the same wavelength, providing redundancy and therefore robustness to the integrated laser diode system.

Docket No. BPHOTO.003

The innovative system disclosed herein has at least two broad applications. First, the system can be operated with some or all cavities being pumped at once, generating and outcoupling up to $2N+1$ wavelengths simultaneously.

5 Each waveguide can be modulated separately (for example, using dc modulation of the pump electrodes, or dc modulation of the coupling electrodes) to generate $2N+1$ uniquely modulated signals, each of a different central wavelength. (Of course, all waveguides need not generate

10 different wavelengths--some could generate redundant wavelengths if desired.)

A second possible broad application includes using the innovative system as a tunable laser source. By pumping only one waveguide gain region at a time, a single

15 wavelength is generated and outcoupled. (For example, if a source generating wavelength $+L5$ is needed, then waveguide $+5$ would alone be pumped.) By only pumping the waveguide with the resonant wavelength desired, any of the multiple resonant wavelengths can be generated. Creating the DBRs

20 of the various waveguides to reflect wavelengths that are closely placed allows a wide range of tunable frequencies to be generated.

These applications are only examples, and are not intended to limit the possible scope of the presently

25 disclosed innovations.

Definitions:

Following are short definitions of the usual meanings of some of the technical terms which are used in the

30 present application. (However, those of ordinary skill

Docket No. BPHOTO.003

will recognize whether the context requires a different meaning.) Additional definitions can be found in the standard technical dictionaries and journals.

5 Chirped Grating: a grating whose period varies over its area;

DBR: Distributed Bragg Reflector;

DFB: Distributed Feedback (Laser);

DWDM: Dense Wavelength Division Multiplexing;

10 GO: Grating Outcoupled (Laser);

HOE: Holographic Optical Element;

LED: Light Emitting Diode;

LD: Laser Diode

15 Modulate: any controlled variation of the signal, including intensity or frequency or phase;

OCG: Outcoupling Grating;

VCSEL: Vertical Cavity Surface Emitting Laser;

Waveguide: a structure which guides the propagation of photons, usually by internal reflection.

20

The description of the present invention has been presented for purposes of illustration and description, and is not intended to be exhaustive or limited to the invention in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art. The embodiment was chosen and described in order to best explain the principles of the invention, the practical application, and to enable others of ordinary skill in the art to understand the invention for

25

Docket No. BPHOTO.003

various embodiments with various modifications as are suited to the particular use contemplated.